Proceedings of the 2009 4th IEEE International
Conference on Nano/Micro Engineered and Molecular Systems
January 5-8, 2009, Shenzhen, China

Etch-back in DDSOG Process by Ultrasonic Agitation and Application to Tunneling Gyroscope Fabrication

Lingyun Wang, Yibo Zeng, Wenwang Li, and Daoheng Sun*

Dept. of Mechanical and Electrical Engineering, Xiamen Univ., Xiamen, Fujian, CHINA

Abstract —**The etch-back of anodic bonded silicon-on-glass wafer using ultrasonic agitation to obtain uniform silicon film and good surface finish in deeply dissolved silicon-on-glass (DDSOG) process has been studied in KOH solution. Etch-back characteristics of p-type (100) 4inch SOG wafer have been explored under the different ultrasonic power. It has been observed that the characteristics of etch-back such as the etch rate, etch uniformity and surface roughness were evidently improved under 120W ultrasonic power agitation. The etching uniformity was less than ±1% on the whole wafer. And the root-mean-square roughness (R_{rms}) of 20.6nm was achieved after 360µm thickness silicon being etched. Some shortcomings of ultrasonic agitation such as damaging membrane and reducing the bonding intensity are observed and how to overcome these disadvantages in DDSOG process is also discussed. Using this technology, a tunneling gyroscope with an out-of-plane, 30µm thickness beam was successfully fabricated.**

Keywords —***DDSOG process, tunneling gyroscope, etch back, ultrasonic agitation, KOH etching.***

I. INTRODUCTION

In the past few years there has been a proliferation of IC-based techniques for the fabrication of micromechanical devices. These processes typically utilize deposited thin films for the device material, limiting their thickness to a few microns. More recently, a high-aspect-ratio is desired to provide sufficient lateral capacitance, to increase the sensitivity of the sensor and to get large proof mass for many microelectromechanical system (MEMS) devices and components, such as comb-drive actuators, inertial sensors and variable capacitors. There are mainly four types of fabrication processes to get high-aspect-ratio suspend silicon structures. They are the SCREAM (single crystal reactive etching and metallization) process, the silicon-on-insulator (SOI) based process, the bulk silicon dissolved wafer process developed by Draper Laboratory and the deeply dissolved silicon-on-glass (DDSOG) process [1-4]. Compared to the dissolved wafer process, the DDSOG process doesn't need the diffusion procedure and directly thins the silicon wafer to the design thickness. So the DDSOG process inherently permits the use of a wide range of thickness of silicon film, which allows for more design flexibility. The etch-back is an important procedure in DDSOG processes, not only to thin the device wafer to the desired thickness, but also to get smooth surface and uniform thickness across the entire wafer [2]. Anisotropic silicon etching technology is widely used to thin the wafer because it doesn't need expensive facility such as chemo-mechanical polishing (CMP) [5]. But it is difficult to obtain uniform roughness and thickness using conventional agitation such as magnetic stirrer, which produced an easily stratified solution and a non-uniform temperature distribution. Especially, pyramidal hillocks are commonly observed on the etch-back SOG wafer, which would fatally affect the latter procedures such as lithograph and DRIE process. Just liking the Fig.1 shown, the comb driver pattern is damaged by the pyramid hillocks. In this paper, ultrasonic waves have been used in etch-back of DDSOG process to promote the characteristic of wet etching [6-9]. And etching morphology has been explored and the effects have been compared. The results show that ultrasonic irradiation is effective to achieve the smooth and defect-free surface with high dimensional uniformity on the whole SOG wafer. Using this technology, we fabricated a tunneling gyroscope with an out-of-plane beam in order to examine effectiveness of ultrasound stimulation in practical device fabrication.

II. EXPERIMENTAL PROCEDURE

The p-type, 4inch, 500µm thickness, 10-20Ω cm-1 (100) double side polished Si wafer and 525µm thickness Prexy 7740 glass were bonded together by anodic bonding. Prior to each experiment, native oxide was removed by a 30s immersion in buffered HF solution, followed by rinsing with DI water. The etch-back apparatus is shown in Fig.2. The ultrasonic transducer could generate 59kHz single frequency ultrasonic waves continuously, the output power and the temperature of the beaker was adjustable. The temperature distribution in the etching beaker could be kept under ±0.5℃ using the circulating water. SOG wafers were supported vertically in a quartz holder and were etched in 45wt% KOH solution at 75℃. For comparing the influence of the different output power of ultrasonic wave on the etch-back results, some others etching conditions such as the temperature and the concentration would be same in all cases presented here. There are two types of SOG wafer being used. One type for investigating the etch-

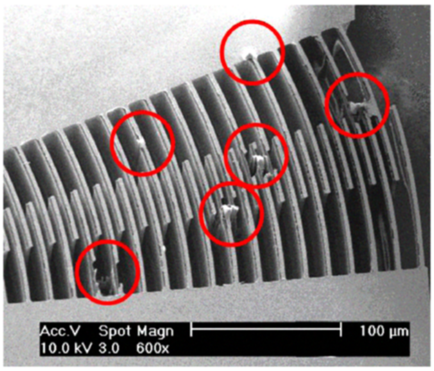

Fig.1 The pyramidal hillocks on the etch-back surface damage the pattern of comb fingners.

This project was funded by Fujian Science and Technology Plan (Projet code: 2002H022).

**Contact author: Sun Daoheng, Professor, Dept. of Mechanical and Electrical Engineering, Xiamen Univ., Tel: 86-592-2185927, FAX: 86-592-2186383, email: sundh@xmu.edu.cn*

978-1-4244-4630-8/09/$25.00 ©2009 IEEE

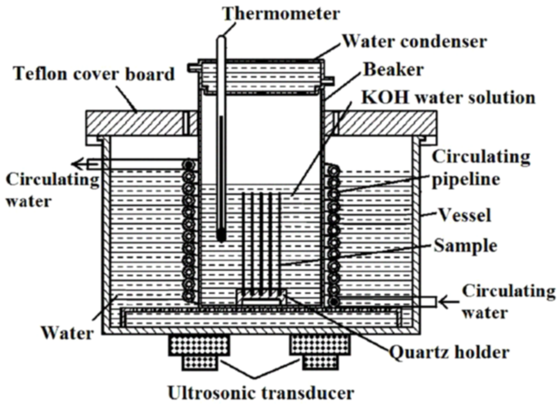

Fig.2 Experiment set-up for etch-back of SOG wafer

characteristics is that one side of the silicon wafer was entirely bonded with glass. The other type for observing the influence of ultrasonic wave on the membrane at the end of the etch-back is that there are some cavities fabricated by RIE etching on the bonding side of the silicon wafer. The etch-back surfaces were inspected and measured with laser scanning confocal microscope (LSCM) and AFM. The etching rate and etch-back uniformity was measured using a micrometer with ±1μm resolution.

III. RESULTS AND DISCUSSION

A. Effect of ultrasonic agitation on KOH etching

Firstly, we used entirely bonded SOG wafer to study the effect of ultrasonic agitation on KOH anisotropic etching, including surface roughness, etching rate, wafer-level uniformity. Fig.3 shows the LSCM images of an Si(100) surface finish of SOG wafer in 45wt% KOH solution at 75℃ for 14 hours etching with different ultrasonic power agitation. As can be seen, a very rough surface was obtained at a lower or higher output power of ultrasonic wave, especially at lower power, and the morphology of orange-peel obviously appeared on the etch-back surface. But smooth pyramid-free surfaces could be obtained at 120W ultrasonic power stimulation. AFM images (Fig.4) ulteriorly validated the above results. Although some hillocks were observed on the etch-back surface at 120W, those dimensions were much smaller and uniform comparing to others output power. AFM could obtain more detail information of surface finish, but LSCM showed outstanding performances in time consumption and scanning area. At the same time, LSCM could get the comparative results with AFM.

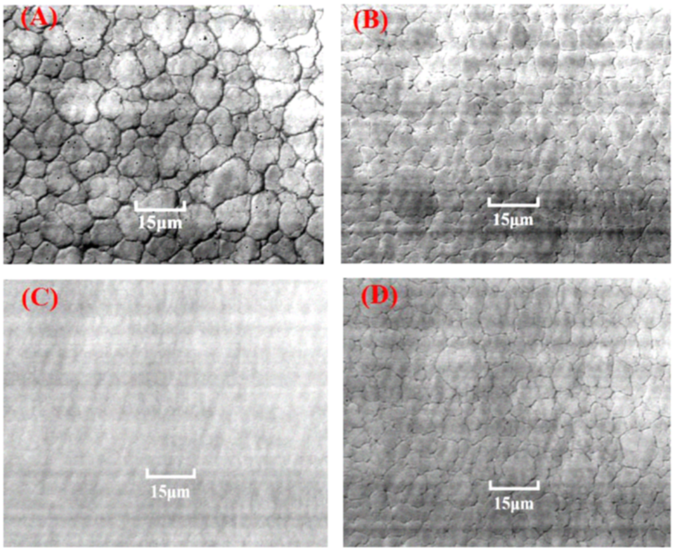

Fig.3 LSCM image of an Si(100) etched surface of SOG wafer in 45wt% KOH solution at 75℃ for 14 hours using different ultrasonic power agitation: (A) 80W, (B) 100W, (C) 120W, (D) 140W.

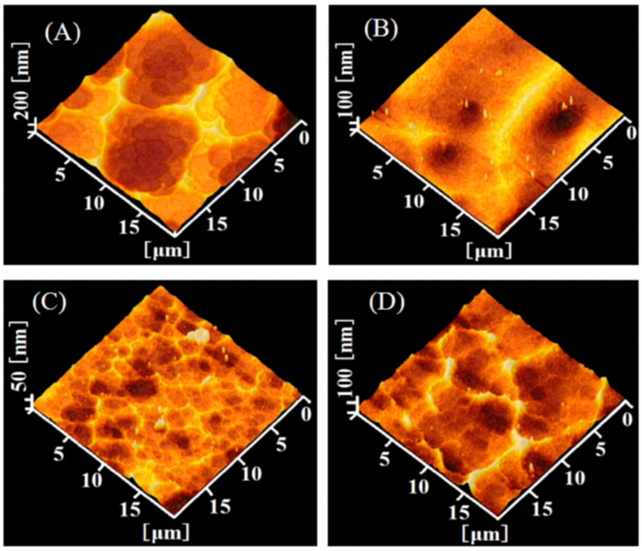

Fig.4 AFM image of an Si(100) etched surface of SOG wafer in 45wt% KOH solution at 75℃ for 14 hours using different ultrasonic power agitation: (A) 80W, (B) 100W, (C) 120W, (D) 140W.

The statistical data (Fig.5) measured by LSCM and micrometer were also consistent with previous results. The surface roughness was promoted when the power was below 120W and the etching rate was linearly enhanced increasing with output power of ultrasonic wave. On the contrary, the surface roughness deteriorated and the etching rate increasing changed very slowly when the power exceeded 120W. This phenomenon may indicate that the diffusion of etchant to the surface and detachment of silicate and hydrogen bubble away from the surface were promoted by ultrasonic agitation at lower power (<120W), and the stronger ultrasonic agitation (>120W) destroyed the balance between the chemical reactions and cavitation effect established at 120W, leading to poor surface roughness. From the slowly changed etching rate at

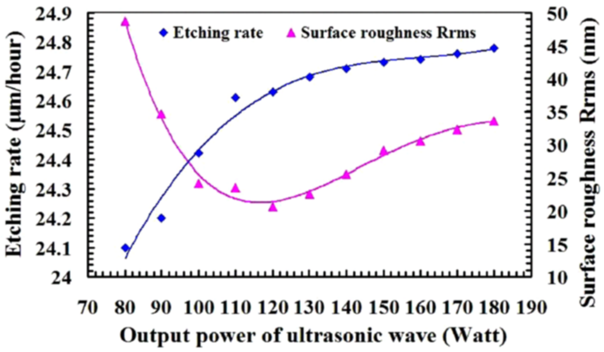

Fig.5 Etching rate and surface roughness against output power of ultrasonic agitation during the etch-back process.

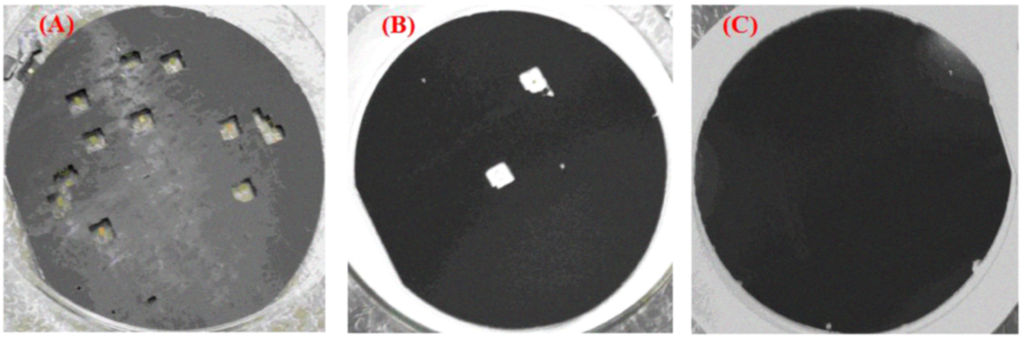

Fig.6 The influence of cavitation effect on the etch-back SOG wafer in the DDSOG process. (A) using 120W ultrasonic power for 16 hours. (B) the first 14 hours using 120W ultrasonic power, the last 2 hours using 80W ultrasonic power, (C) the first 14 hours using 120W ultrasonic power, then the last 2 hours using 55wt% KOH solution and shutting down the ultrasonic power.

high power ultrasonic agitation, we also could conclude that the etching rate was only determined by the chemical reactions themselves. However, the effectual output power is strongly dependent upon the geometry of the vessel and even the water level of the washer bath, that is, different apparatus might have different characteristics.

The 4inch bonded SOG wafer after 14 hours KOH etching was measured to verify the wafer-level etching uniformity. Eight regions evenly spaced over the wafer were chosen to measure the residual thickness of SOG wafer using the micrometer. Difference between the maximal and the minimal thickness was employed to determine the etching uniformity. As can be seen from Table1, wafer-level uniformity below ±1% has been achieved with the ultrasonic agitation, which is completely satisfied with many requirements of MEMS devices. The enhancement of wafer-level etching uniformity is attributed to the elimination of the stratification of the etchant and the temperature in the beaker. In addition, with ultrasonic stirring, the diffusion procedure of silicate particles is significantly accelerated. Consequently, uniform etching thickness can be achieved with the consistent etching rate in the long-term etching.

B. *Disadvantage of ultrasonic agitation to the DDSOG process*

In succession, the SOG wafer with cavities on the bonding side was chosen to simulate the DDSOG process. The SOG wafer could be thinned to about 100μm residual thickness for 14 hours etch-back at the previous conditions. The membrane have been broken by 120W ultrasonic agitation all the time (Fig.6 (A)), even the power reduced to 80W (Fig.6 (A)) at the end of 2 hours etching. Shutting down the ultrasonic and using 55wt% KOH solution at ultimate two hours could overcome this shortcoming. Smooth, "mirror-like" surface has been achieved (Fig.6 (C)). As above mentioned, the ultrasonic stirring could improve the surface roughness and the wafer-level uniformity at certain output power. But the ultrasonic wave would damage the membrane structure. Using high molarity KOH solution and adding isopropyl alcohol (IPA) to the solutions maybe improve the surface quality and eliminate the shortcoming of membrane break [10-11]. However, it is difficult to get uniform structure for the long-term etching. Therefore, applying ultrasonic agitation at the beginning of the etching and using high concentration KOH etchant at the end of etch-back in DDSOG process could insure the smooth surface finish and uniformity etching.

TABLE I. RESIDUAL THICKNESS OF SOG WAFER

Residual Thickness	**Eight Regions**							
	1	*2*	*3*	*4*	*5*	*6*	*7*	*8*
SOG wafer (μm)	644	646	644	645	644	645	645	644

We also found that the bonding intensity was decreased by ultrasonic force for long-term ultrasonic agitation. The bonding interface of the SOG wafer was very compact before ultrasonic agitation (Fig.7 (A)), but after ultrasonic agitation for 14 hours etching the separate gap on bonding area was observed because interference of light appeared in the bonding interface (Fig.7 (B)). For overcoming this shortcoming, the thickness of electrode on the surface of glass must be limited within 150nm and larger bonding areas are also recommended [12].

C. *Application of DDSOG process in tunneling gyroscope fabrication*

Based on above experiment, a tunneling gyroscope with an out-of-plane, 30μm thickness beam was successfully fabricated using DDSOG process. The process started with (100), heavily p-doped 4 in. silicon wafers. After shallow trenches about 1μm were etched by ICP etching (Fig.8 (A)), the silicon tip was etched through RIE technology (Fig.8 (B)). A Ti/Pt/Au layer with thickness of about 200nm was sputtered onto silicon tip (Fig.8 (C)). A Ti/Pt/Au layer with thickness of about 130nm was also sputtered on Pyrex glass, and pattered using lift-off to form interconnection electrodes(Fig.8(D)), followed by silicon and glass wafers anodic bonding at 380℃,800V and 1atm.

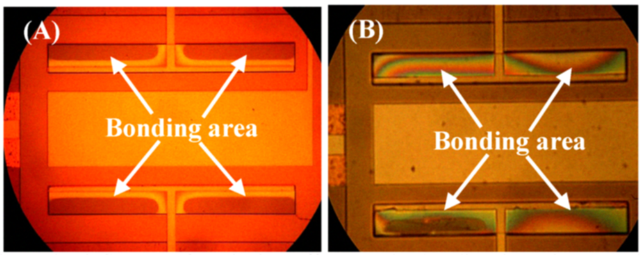

Fig.7 The influence of cavitation effect on the bonding intensity. (A) the bonding interface before using ultrasonic wave, (B) the bonding interface after using ultrasonic agitation for 14 hours.

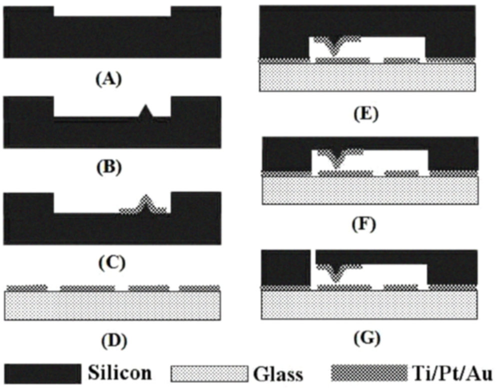

Figure.8 Fabrication process of the tunneling gyroscope. (A) shallow trench etching to defined the original gap between the tip and the detected electrode, (B) etching the tunneling tip by RIE, (C) sputtering the Ti/Pt/Au on the tip surface, (D) interconnection electrode defined by lift-off technology, (E) anodic bonding between the silicon wafer and the glass substrate, (F) silicon wafer thinning, (G) DRIE to form and release the device.

ambient in a AWB04 wafer bonder (Applied Microengineering Ltd, England) for 60 min (Fig.8 (E)). Silicon wafers were thinned to the designed thickness by KOH etching with ultrasonic agitation at the beginning etching and then with high concentration solution at the end of etching (Fig.8 (F)).Finally, structures were formed and released by DRIE process (Fig.8 (G)). SEM picture of gyroscope are shown in Fig.9 (A) and a close-up view in Fig.9 (B). Compared to the previous fabrication result (Fig.1), there is no pyramid hillocks presented on the structure surface. DDSOG process allows the creation of high-aspect-ratio single crystalline-silicon structures, enabling the fabrication of devices with high electrical and mechanical performance. In contrast to poly-silicon material, there is no residual stress in it. Moreover, to obtain high sensitivity, the bulk mass is always hoped to be as large as possible.

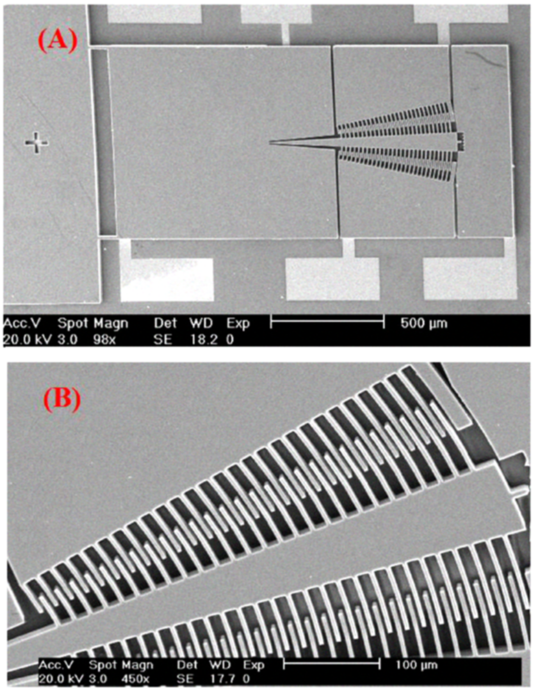

Fig.9 the fabrication of tunneling gyroscope using DDSOG process. (A) the SEM image of tunneling gyroscope, (B) the close-up view of comb fingers

IV. CONCLUSIONS

The etch-back of anodic bonded silicon-on-glass wafer in DDSOG process has been studied in KOH solution using ultrasonic agitation to obtain uniform silicon structure and smooth surface finish. Etch-back characteristics of p-type (100) 4inch SOG wafer have been explored under the different ultrasonic power. It has been observed that the characteristics of etch-back such as the etch rate, etch uniformity and surface roughness were evidently improved under 120W ultrasonic power agitation. The etching uniformity was less than ±1% on the whole wafer. And the root-mean-square roughness (Rrms) of 20.6nm was achieved after 14 hours etching. Some shortcomings of ultrasonic agitation such as damaging membrane and reducing the bonding intensity are observed and how to overcome these disadvantages in DDSOG process is also discussed. Using this technology, a tunneling gyroscope with an out-of-plane, 30µm thickness beam was successfully fabricated.

ACKNOWLEDGMENTS

The authors would like to thank Pen-Tung Sah Micro-Electro-Mechanical Systems Research Center of Xiamen University for the fabrication of the microgyroscopes.

REFERENCES

[1] WD Sawyer, MS Prince, GJ Brown, “SOI bonded wafer process for high precision MEMS inertial sensors,”Journal of Micromechanics and Microengineering, 15(2005), pp:1588-1593.

[2] J. Chae, H. Kulah and K. Najafi, A hybrid silicon-on-glass (SOG) lateral micro-accelerometer with CMOS reasout circuitry. Proc.2002 MEMS Conf. pp:623-626.

[3] T.E. Bell and K. D. Wise, “A dissolved wafer process using a porous silicon sacrificial layerand a lightly-doped bulk silicon etch-stop” Proc. IEEE MEMS, Heidelberg, Germany, 1998, pp:251-256.

[4] YB. Gianchandani, K.Najafi., “A Bulk Silicon Dissolved Wafer Process for MicroelectromechanicalDevices”, Journal of Microelectromechanical Systems, vol. 1, No. 2, Jun.1992, pp. 77-85.

[5] J.A. Plaza, J. Esteve and E. Lora-Tamayo, “Simple technology for bulk accelerometer based on bond and etch back silicon on insulator wafers”, Sensors and Actuators, Physics A, vol. 68, 1998, pp. 299-302.

[6] Chii-Rong Yang, Po-Ying Chen, Yuang-Cherng Chiou, “Effects of mechanical agitation and surfactant additive on silicon anisotropic etching in alkaline KOH solution”, Sensors and Actuators, Physics A, vol. 199, 2005, pp:263-270.

[7] T. Baum and D.J. Schiffrin, “AFM study of surface finish improvement by ultrasound in the anisotropic etching of Si <1 0 0> in KOH for micromachining applications”, J. Micromech. Microeng., vol.7, 1997, pp. 338–342.

[8] E.D Palik, O.J Glembocki, I. Jr Heard, P.S Burno and L. Tenerz, “Etching roughness for (100) silicon surface in aqueous KOH” J. Appl. Phys., vol. 70, 1991, pp:3291–300.

[9] J. Chen, L. Liu, Z. Li, Z. Tan, Q. Jiang, H. Fang, Y. Xu and Y. Liu, “Study of anisotropic etching of (1 0 0) Si with ultrasonic agitation”, Sens. Actuators, A, vol 96, 2002, pp. 152–156.

[10] E. Palik, O. Glembocki, “Etching roughness for (100) silicon surface in aqueous KOH”, J. Appl. Phys, vol 70, 1991, pp:3291-3300.

[11] I.Zubel, I.Barycka, K. Kotowska, M. Kramkowska, “ Silicon anisotropic ething in alkaline solutions IV, the effect of orgnic and inorganic agents on silicon anisotropic ething process”, Sens. Actuators A, vol 87, 2001, pp: 163-171.

[12] W.P.Maszara, B.L. Jiang， A. Yamada, et al, “Role of surface morphology in wafer bonding”, J.AppL Phys., 1991, vol 69, pp:257-260.